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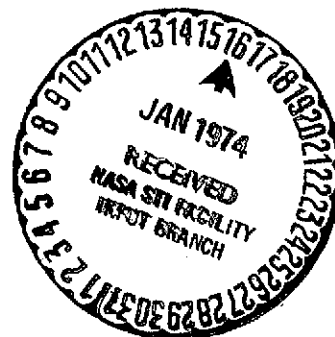
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### SUMMARY

This report describes the results of a feasibility study to design and demonstrate solid-state switchgear in the form of circuit breakers and a power transfer switch. The switchgear operates on a nominal 270 V dc circuit and controls power to a load of up to 15 amperes. One circuit breaker may be interconnected to a second breaker to form a power transfer switch. On-off and transfer functions of the breakers or the transfer switch are remotely controlled. A number of reclosures with variable time delay between tripout and reclosure are programmed and controlled by integrated analog and COSMOS logic circuits. A unique commutation circuit, that generates only minimal transient disturbance to either source or load, was developed to interrupt current flow through the main SCR switching element. Laboratory tests demonstrated performance of the solid-state circuit breakers over specified voltage and temperature ranges.

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## BACKGROUND

High voltage dc electric power systems (above 100 V dc) are seriously being considered as candidate systems for future generation air and spacecraft. Recent NASA sponsored studies and investigations by DOD agencies show that high voltage dc transmission and distribution can provide significant weight reduction, greater design flexibility, higher reliability, and lower cost than conventional 28 V dc or 115 V ac systems. The optimum dc system voltage appears to be about 300 V dc when all factors are considered including corona breakdown. System voltages ranging from 120 to 300 V dc are being recommended as having maximum advantages, in general, and therefore are the most desirable for future development.

Several significant technology problem areas that impede the application of these high voltage concepts to electric power systems have been identified. One of the principal problem areas is the need for demonstrated, space rated, power control and protection devices for power electronic circuits and systems. Optimum system concepts may require automatic power management using advanced concepts of remote control, status reporting, and display as obtained by coupling computer multiplexing techniques, with the remote control concept. This approach will provide faster reaction times while minimizing transmission and distribution wire lengths. In addition it should provide increased reliability and flexibility for system supervision, reconfiguration and check-out.

The continued and increasing complexity of modern aircraft and spacecraft places greater demands on the performance of electric power circuitry. These demands require consideration of much more rapid fault sensing and reaction to protect electrical and electronic equipment. Circuit breakers should protect both the power transmission cables and associated loads, circuits, and components, which are a part of the power system. Currently available electromechanical switch-gear suffer from limited reliability and from functional limitations. Their high failure probability due to contact erosion limits reliability. The functional limitations include relatively slow response times (the order

of milli-seconds to seconds), difficulty of maintaining trip calibration, and the need for manual operation of power transfer switches.

Solid state circuit breakers (SSCBs) offer great potential for high reliability, long life, fast response, and remote operation. They not only operate much faster than conventional breakers (by orders of magnitude), but they also perform thousands of times more load current interruptions without requiring maintenance. The SSCBs do not create arcing or hot gases during operation. In addition they lend themselves conveniently to remote operation by low-energy electrical signals and to compatibility with computer control.

This report describes the results of a feasibility study to design and demonstrate solid state switchgear in the form of circuit breakers and a power transfer switch for use in a 270 V dc power circuit. This study has established the feasibility of solid state switchgear and has defined a basic design suitable for inclusion in power system tests. These tests can thus determine the parameters and specifications that must necessarily be included in subsequent designs for future aircraft and/or spacecraft development. These developments have potential applications to such programs as Space Shuttle, Space Station, and advanced performance aircraft.

For this feasibility study 270 V dc was chosen as being compatible with direct full-wave rectification of available aircraft alternators. The alternators could conceivably be run at variable speeds, saving the weight and cost of constant-speed drives, which also have a short operational life. Also, 270 V dc was considered to be a practical source voltage to be obtained from either solar arrays or fuel cells on spacecraft.

Since this was a feasibility study, many features were included to provide information relative to performance of switchgear that might be desirable for future systems. Whereas only a few of these requirements may be simultaneously incorporated in any one device for future missions, many of them have served to establish limits on performance for new designs. Thus, solid state circuit breakers having the following unique characteristics have been designed, built, and tested:

- (1) Carry a continuous dc current up to 15 A in a supply line at 270  $\pm$  27 V dc;
- (2) Trip out at an adjustable current level of 18 to 45 A;
- (3) React to transient overloads below the ultimate trip level on an energy basis proportional to  $I^2t$  within the limits  $5 < I^2t < 30$ ;
- (4) Provide programmable 0 to 9 automatic resets with adjustable delay times of 1.5 to 100 ms between resets;
- (5) Have a forward voltage drop of less than 3 V dc with a load current of 15 A;
- (6) Provide operation from isolated low-energy remote control signals of less than 1 millijoule;
- (7) Perform all functions in the presence of transient overvoltages up to 300 V above line voltage for a 10  $\mu$ s duration;
- (8) Operate over a temperature range of -45 to 100<sup>o</sup> C;
- (9) Provide isolation from susceptibility to malfunctions due to extraneous voltages, currents, and EMI;
- (10) Connect to form a power transfer switch operating in the "break before make" mode.

## DESIGN CONCEPT

The concept of the logic-controlled solid-state circuit breaker is illustrated by the block diagram shown in figure 1. The power from the 270 V dc source is fed through the solid-state switching element and then through a current sensor into the load. An analog circuit determines whether the sensed current represents an overload. If an overload is sensed, the analog circuit then sends a trip signal to the power switching circuit. A logic circuit provides on-off command functions and isolation, together with all timing, reset, and recycle counting related to automatic reclosure. An internal electronic power supply provides all the internal operating voltages. Each of these functional blocks is discussed in the following paragraphs.

## SWITCHING CIRCUIT

From a circuit design standpoint, it would be desirable to place the power switching element in the return lead and to maintain this lead at ground potential. However, since the circuit breaker was necessarily general purpose, and since it was necessary to insure that the load could be grounded by grounding the power return, the switching element was placed in the +270 V dc line.

Due to the high voltage requirements ( $270 \pm 27$  V) and the nominal current of 15 A with overloads up to 45 A specified, the main solid state switching element was determined to be a silicon controlled rectified (SCR). Selection of the main-switching SCR involved a number of requirements which had to be considered collectively. High blocking voltages were an initial requirement, because any conceivable switching operation involved transients that could be several times the source voltage. Fast recovery devices were essential to insure turn-off with a minimum of energy storage and/or loss. SCRs with fast recovery were also required to comply with the one millisecond recycle time.

In order to turn off an SCR, it is necessary to reduce the current flowing through it to a low value (sub-holding current) or, more preferably to a zero-current condition. This can be conventionally achieved by applying a reverse potential for a time sufficiently long to allow the device to recover its blocking capability. The basic circuit for forced-commutation is shown in figure 2.

Numerous approaches toward commutation were evaluated and discarded for various reasons. The major problems were either that the energy of commutation had to be dissipated through the load (the case with the circuit shown in figure 2), or that voltages developed across the SCR or the commutation capacitor during the commutation cycle were excessive. The basic commutation circuit eventually used in the circuit breaker is shown in figure 3.

Assume that SCR-1 is gated on and carrying load current. The capacitor C1 is pre-charged to approximately 450 volts in the polarity indicated. Reference is now made to figure 4 to illustrate the operation of the commutation circuit.

In the event of an external turn-off command, or a sensed over-current generated trip signal, SCR-2 is gated on. This occurs at time  $t_0$ . SCR-2 dumps the commutation capacitor across the winding  $L_1$  to the transformer driving the anode of SCR-1 rapidly negative and turning it off. The solid state circuit breaker is now open.

The current flowing through  $L_1$  prior to  $t_0$  continues to flow but is now diverted through SCR-2 and into the capacitor initially aiding its discharge. As the capacitor discharges, the negative voltage on the anode of SCR-1 approaches zero at time  $t_1$  on the curve. The anode of SCR-1 has now been held negative long enough that the SCR will not conduct with a forward applied voltage unless it is again gated on. The current through  $L_1$  continues to flow and the capacitor continues to discharge until  $C_1$  voltage goes through zero at time  $t_2$ .

Inductor current in  $L_1$  is now at maximum value. SCR-3 is gated on at this point, enabling current flow through commutation transformer winding,  $L_2$ .  $L_1$  and  $L_2$  have essentially the same number of turns, so that with the same magnetic field, the current rapidly drops to approximately one-half the peak value of current. The period of oscillation for the commutation circuit ( $C_1, L_1, L_2$ ) is now approximately doubled, beginning with time  $t_2$ .  $C_1$  voltage, rising in the positive-going direction, now appears across  $L_1$  and  $L_2$  in series. Half of this voltage appears across SCR-2 as reverse bias, turning SCR-2 off. This voltage is approximately equal to the voltage across SCR-1. Note that this SCR-1 voltage is approximately half the value it would have reached if SCR-3 did not conduct. This conduction of SCR-3 thus permits lower voltage ratings for SCR-1.

As oscillation continues, the commutation current (capacitor  $C_1$  current) goes through zero and SCR-4 is gated on at time  $t_3$ ; capacitor  $C_1$  is charged to a voltage that represents the energy of the initial  $C_1$  charge, plus the energy stored in the commutation inductor  $L_1$  at time  $t_0$ , neglecting circuit losses.

At time  $t_4$ , the capacitor  $C_1$  voltage is again going through zero in the negative direction, the voltage across SCR-1 is back down below source voltage, and SCR-4 is carrying maximum current. By time  $t_5$ , capacitor  $C_1$  is nearly recharged (neglecting circuit losses), SCR-4 is

turned off, and SCR-1 anode voltage returns to source voltage.

Circuit energy loss during commutation is compensated by recharging capacitor  $C_1$  during the latter portion of the commutation cycle, beginning this recharge following time  $t_4$  and continuing recharge until  $C_1$  is fully recharged. The entire commutation cycle requires less than 0.5 ms (neglecting some additional recharge time required), and occurs with minimum reference to the return circuit of the power source (with exception of recharge), in order to create minimum transient disturbances.

A continuous gate drive is provided for the main switching element, SCR-1. This gate drive insures that SCR-1 will remain ready to conduct at all times while the circuit breaker is on, even through the load current may go to zero. Gate circuitry was also required to provide gate pulses to control each of the SCRs during the commutation. Detailed descriptions of each of these circuits are available in the final report of the contract, NASA CR-121140.<sup>1</sup>

Since it is possible that the main SCR might close into a short-circuit or other load fault condition, all necessary conditions for assuring commutation must exist before SCR-1 is gated on. The commutation capacitor must be fully precharged before turning on SCR-1 and thus closing the circuit breaker into a load or a fault. Since the commutation capacitor must be precharged using negative voltage, an isolated output from the internal power supply of the circuit breaker was provided for this purpose.

The charging circuitry for the commutation capacitor must be capable of withstanding the high voltage occurring between the commutation capacitor and the charging source during the commutation cycle. Various LC filter approaches were investigated, but were found to be impractical. The most satisfactory approach to this problem is shown in figure 5 and is the one used in the final breaker design. In this approach the negative charging output of the breaker power supply is used with additional circuitry as a constant-current source for precharging the commutation capacitor. A transistor isolation switch used in the negative output of this constant current source is opened during the commutation cycle, thereby isolating the charging source from the commutation bus during the high



voltage portion of the cycle. The isolation switch is driven by the voltage sensing network through a gate that closes the isolation switch during the precharge interval. Shortly after the onset of a commutation cycle the isolation switch is opened and is not reclosed until after commutation is accomplished near the end of the commutation cycle.

## CURRENT SENSING

Current was sensed on the load side of the power switching element in order to provide greater accuracy in analog fault sensing. A Hall effect device was originally considered for this application as it would provide the necessary current indication and also provides high voltage isolation between the power circuitry and the overload detection circuitry. A second Hall device, driven by the amplified output of the first Hall device, provided the  $I^2$  function which was fed to an integrator to produce  $I^2t$  integration. However, manufacturing tolerance of the Hall devices imposed the requirement for tailoring each circuit in order to compensate for offset, temperature, and drift. This made the use of Hall effect devices impractical from the standpoint of economy in subsequent production and testing.

A series resistor was therefore selected as the more practical sensing element. In order to minimize inductance, a coaxial shunt was used. Use of the shunt entailed operation of the complete analog overload detection circuit at high load potential; that is, at +270 volts when the breaker was on, and at or near zero when it was off. The shunt could not be put in the load return lead because there was no surety of what grounding approach would be used in a system in which the breaker might be connected, or where a fault might occur.

The voltage output of the current sensing shunt was fed to analog circuitry which provides the  $I^2t$  and ultimate current trip levels as illustrated in figure 6. The sensed current value is amplified and then compared with a reference signal representing the desired ultimate trip threshold level. Selectable reference levels were provided for ultimate trip ( $I_L$ ) thresholds corresponding to currents of 18 to 45 amperes in

seven discrete steps.

In addition to ultimate trip functions, the analog circuitry provides for  $I^2t$  fault sensing. The amplified signal proportional to sensed current is squared and then fed to an integrator which provides the  $I^2t$  value. This is then compared with a reference voltage corresponding with a predetermined  $I^2t$  value. If this  $I^2t$  level exceeds the reference level, a trip signal is initiated.

In order to prevent integration at all current levels, a reference level corresponding to 15 amperes is subtracted from the squaring/integration circuitry so that the circuit response approximates the integral,  $\int (I^2 - 15^2) dt$ . It is basically assumed that the load circuitry of the switch gear output is capable of 15 amperes sustained current, so that  $15^2$  amperes<sup>2</sup> is proportional to the allowable thermal dissipation of load circuitry.

A unique circuit was designed in which an approximation to analog squaring and integration was accomplished with one operational amplifier. Reference is made to the simplified integrator diagram (fig. 7). When the input voltage,  $V_{IN}$ , is low so that  $I_{IN}$  is less than  $I_{REF}$ , the net input to the operational amplifier is negative. The output of this amplifier, attempting to go positive, is clamped at approximately 0.5 V by diode D1; the circuit is now in the off state. When  $V_{IN}$  is raised by an increase in sensed current,  $I_{IN}$  can exceed  $I_{REF}$ , with the result that the output starts going negative as capacitor C2 charges toward the  $R_F(I_{REF} - I_{IN})$  with a time constant  $R_F C2$ . This operation is shown graphically in figure 8. Thus far, this circuit integrates, but does not square the input voltage.

The effect of directly squaring the integrator input voltage would be to cause higher current-analog voltages to produce a faster trip than the simplified integrator circuit provides. This same effect is indirectly produced by starting the feedback capacitor charging with the output already offset in the negative direction by a value of voltage proportional to the sensed current as shown in the diagram of figure 9.

The voltage offset proportional to the sensed current is obtained by applying the voltage from the current-sensing shunt directly to the non-inverting input of the operational amplifier. This circuit diagram is shown in figure 10.

The desired response time versus sensed current is approximated through appropriate selection of reference voltages, resistance, gains, and time constant. The fastest allowable response is used, considering component tolerances and drift. Long delays cause unnecessary heating of the main SCR; particularly when multiple resets and reclosures of the SSCB occur. In the preceeding discussion of the integrator circuit, the charging of the feedback capacitor to approximately +0.5 V in the off condition has been ignored. The three diodes D2, D3, and D4 provide compensation for this occurrence.

In the off condition, the output terminal of the operational amplifier is still at +0.5 V, but D3 and D4 have insufficient voltage applied across them to reach the knee of their voltage-current characteristic. This blocking state leaves a negligible charge on the feedback capacitor C2, making the output voltage essentially zero.

When  $I_{IN}$  exceeds  $I_{REF}$ , diode D2 conducts and the feedback capacitor begins to charge. In this case, diode D1 becomes reverse-biased. Diode D2, in the feedback loop, has a negligible effect on circuit performance. When  $I_{IN}$  is again reduced to less than  $I_{REF}$ , the output voltage returns toward zero due to discharge of the feedback capacitor through diodes D3 and D4 until the output voltage approaches zero. Because these two diodes are in the feedback loop until diode D1 clamps the output, diodes D3 and D4 likewise have a negligible effect on circuit performance.

The response of the current sensor and analog circuits is illustrated by the curve of figure 11. The dotted lines with data points included represent the experimentally determined variation in response over the extremes of temperature and voltage. This total variation of only a few percent is not only in agreement with theoretically predicted design limits, but also is well within the  $I^2t$  lines at 5 and 30 A<sup>2</sup>.s, which were initial contract requirements.

## POWER SUPPLY

The electronic power supply receives its operating voltage from the 270 V dc input line and provides the circuit breaker operating voltages of  $\pm 12$  V dc for analog and logic circuits, SCR-1 continuous gate voltage, -200 V dc for the commutation capacitor precharge and recharge circuit. While most of the power supply design is conventional, it is critical that adequate voltage isolation between different portions of the power supply circuitry be maintained.

## LOGIC CIRCUITS

The overall operation of the circuit breaker is controlled by logic circuitry that relates the time and order of each operational function required. There are some 14 separate steps or sequences provided as illustrated by the functional block diagram for the logic portion of the circuit breaker shown in figure 12. This circuitry provides the isolation between control signal inputs and power being controlled as well as all required timing and counting functions. COSMOS integrated circuits were chosen for the logic, because of their relatively high noise immunity. The number and complexity of the logic functions was a direct result of the many variable requirements for which feasibility was to be demonstrated.

## BREAKER OPERATION

The logic operation and its control of the breaker is best described by an overall functional description of the complete circuit breaker. We refer to the more detailed circuit breaker block diagram in figure 13 for aid in this description.

A manual close command given to the SSCB causes the power supply to begin switching. Immediately a 12 V output, fed to the power up-reset circuitry, sets all logic to the initial state and prevents SCR-1 from being gated on. Built-in integration circuitry insures a 0.1 second delay between the manual close command and the initial clear signal. This delay

allows enough time for all critical voltage levels to stabilize. Now, when the initial clear signal arrives, SCR-1 gates on closing the SSCB into the load.

Before SCR-1 fires, however, the SSCB must be ready to open under fault-trip conditions in case a short circuit or other overload condition exists at the load. To insure a readiness for action several conditions must be set up during the 0.1 second power up-reset interval. These conditions are:

- (1) All power supply output voltages stabilized at operational levels;
- (2) All analog and logic circuits armed and ready to respond to sensed overload and fault-trip output signals;
- (3) The commutation circuit ready to commutate with capacitor C1 fully precharged.

With the SSCB closed and a load current flowing assume an over-current,  $I_L$ , or an  $I^2t$  fault condition is sensed for the first time. Here's what happens simultaneously:

- (1) A trip signal through the comparator fires the SCR-2 gate starting the commutation cycle;
- (2) Another signal removes the continuous gate drive from SCR-1;
- (3) The programmable timer and the counter reset timer both start counting time.

When SCR-1 is off and the programmable timer count ends, the following events happen all at once:

- (1) The continuous gate drive is reapplied to SCR-1;
- (2) A gate firing pulse is also applied to SCR-1 turning it on;
- (3) The recycle counter counts "one".

If the fault still remains on the load, this cycle repeats until either the fault clears or the recycle counter reaches its programmed count setting.

So, if the fault clears, SCR-1 remains on. After 102 seconds the counter reset timer turns the recycle counter back to zero. A later fault will then start a complete new cycle.

However, if the fault persists and the recycle counter reaches its full preset count, then SCR-1 remains off. The SSCB is now open and remains

so until a manual close command is again applied to it. With the SSCB open a logic command disables the internal power supply.

### SSCB CONSTRUCTION

The circuit breakers are built on a main frame supporting the main SCR on its heat sink and the individual discrete components of the commutation circuit. The majority of the circuitry is placed on three PC boards, one each for the power supply, for the gate and recharge circuits, and for the analog and logic circuits. The power and gate boards were conformal-coated because of high voltages. Figure 14 is a photograph of the assembled breaker without its cover. Its dimensions are about 18 cm per side and its weight (cover included) is about 3 kg.

### TESTING

The performance of each PC board was measured before it was wired into the final assembly. Timer settings, ultimate current trip levels, and the  $I^2t$  thresholds were set and calibrated. After complete assembly each breaker was tested operationally as follows:

- (1) Response to external close and open commands;
- (2) Series voltage drop at 15 A;
- (3) Response time for  $I^2t$  trip and recycle time;
- (4) No trip response checked for transient overloads less than pre-set trip levels.
- (5) Ultimate trip response measured for 45 A at 243 V and 18 A at 297 V.

All tests were run on a special system test tool built for this program. A simplified schematic of the test tool is shown in figure 15. The results of the operational tests are shown on the curves of figure 16 to permit easy comparison of the five individual circuit breakers. Please note that the time to trip for the ultimate current trip tests is, in reality, the time it took the current to rise to the trip level. This is more a function of circuit inductance than of breaker performance. The trip time after reaching the ultimate trip level was only a few microseconds. Polaroid

photographs of oscilloscope traces provided data for recording both current levels and time to trip.

The total power loss is estimated to be less than 55 watts at full load, i. e., 270 V and 15 A dc. Of this total 45 watts is due to the 3 V forward drop at 15 A. The additional 10 watts of loss was not measured, but is estimated to include power losses in the following circuits: power supply, SCR-1 continuous gate drive, capacitor recharge, and analog/logic power.

The breakers were characterized by a series of tests in two general areas:

- (1) Several 150 V, 10  $\mu$ s pulses were superimposed on the 270 V dc line to test transient susceptibility. The breakers did not close when open and remained closed in the presence of the voltage transients;
- (2) Breaker thermal response was measured by testing in a thermal control chamber at temperatures of 25, 50, 0, -45, 100° C in that order. Operational responses were observed and measured at each temperature setting.

Thermal test data is shown in figure 17. One thousand cycle life tests were made on three breakers, one each at 0, 25, and 50° C. Operation of two interconnected breakers to form a power transfer switch was tested with both breakers performing their normal functions. The command to turn on, with the other breaker on, did result in a break-before-make operation.

## CONCLUSIONS

We have proven the basic feasibility of developing a solid-state circuit breaker and transfer switch to operate in a 270 V, 15 A dc circuit. The technology for using SCRs in the solid-state switchgear circuit design now exists. Circuit breakers using SCR switching elements have been designed, built, and tested. They have met or exceeded most of the original designated performance characteristics. These circuit breakers with their automatic trip, their recycle capability, and remote control, can

be interconnected to provide a remote controlled transfer switch with overload protection.

Solid-state switchgear having different current or voltage requirements, as determined by aircraft or spacecraft electric power system analyses, can be built using present-day SCR and transistor switching elements. As further advances are made in power transistors or gate-controlled switches, simplified circuits can be built to give better performance with less complexity and higher reliability. Improvements in the stability of Hall-effect devices or linear analog photoisolators could greatly improve future solid-state breakers. Ultimately remote control by a computer could replace most of the unique logic circuitry developed in this program and thereby simplify the breaker design.

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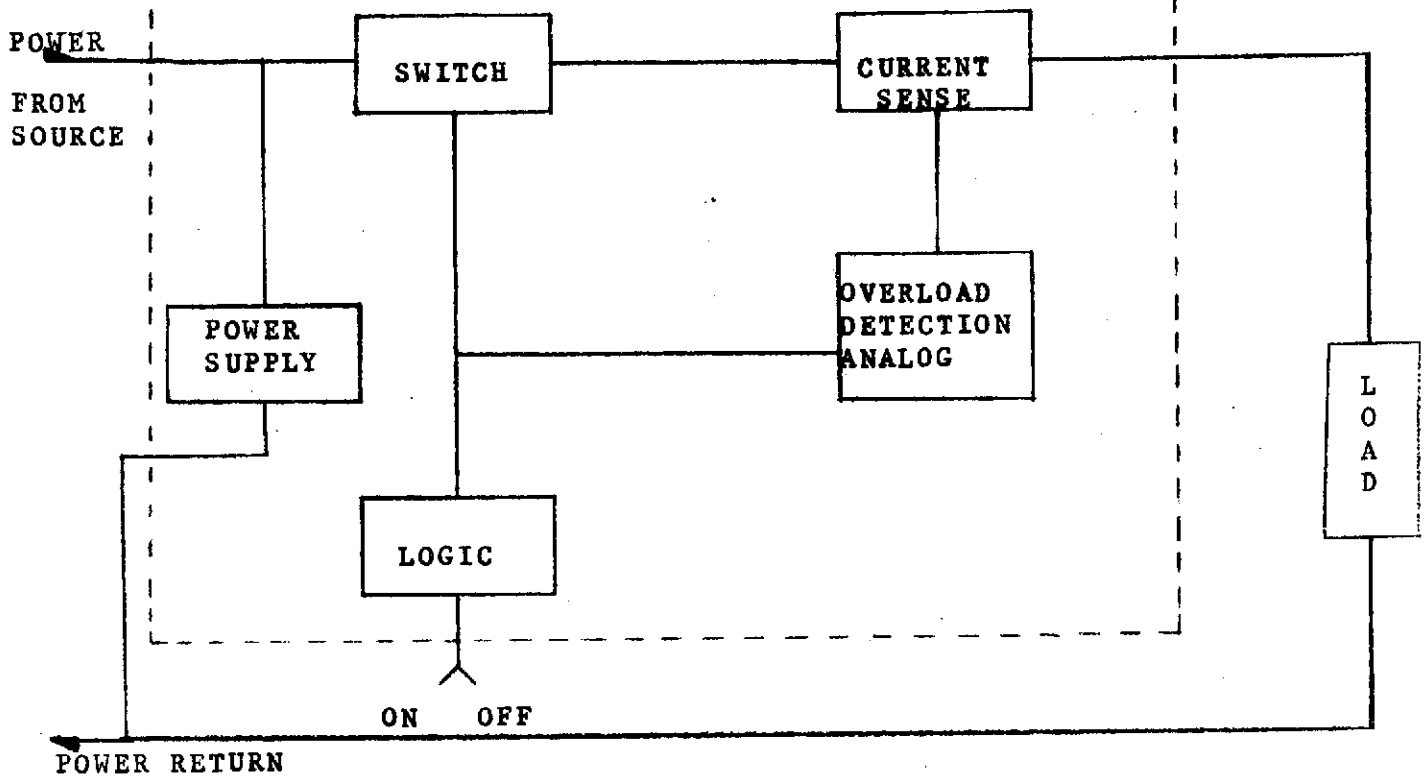


Figure 1 - Block Diagram, Logic Controlled Circuit Breaker

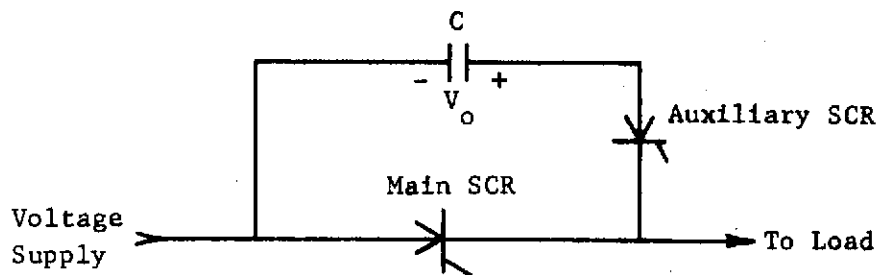


Figure 2.- Direct-Coupled Forced Commutation Circuit

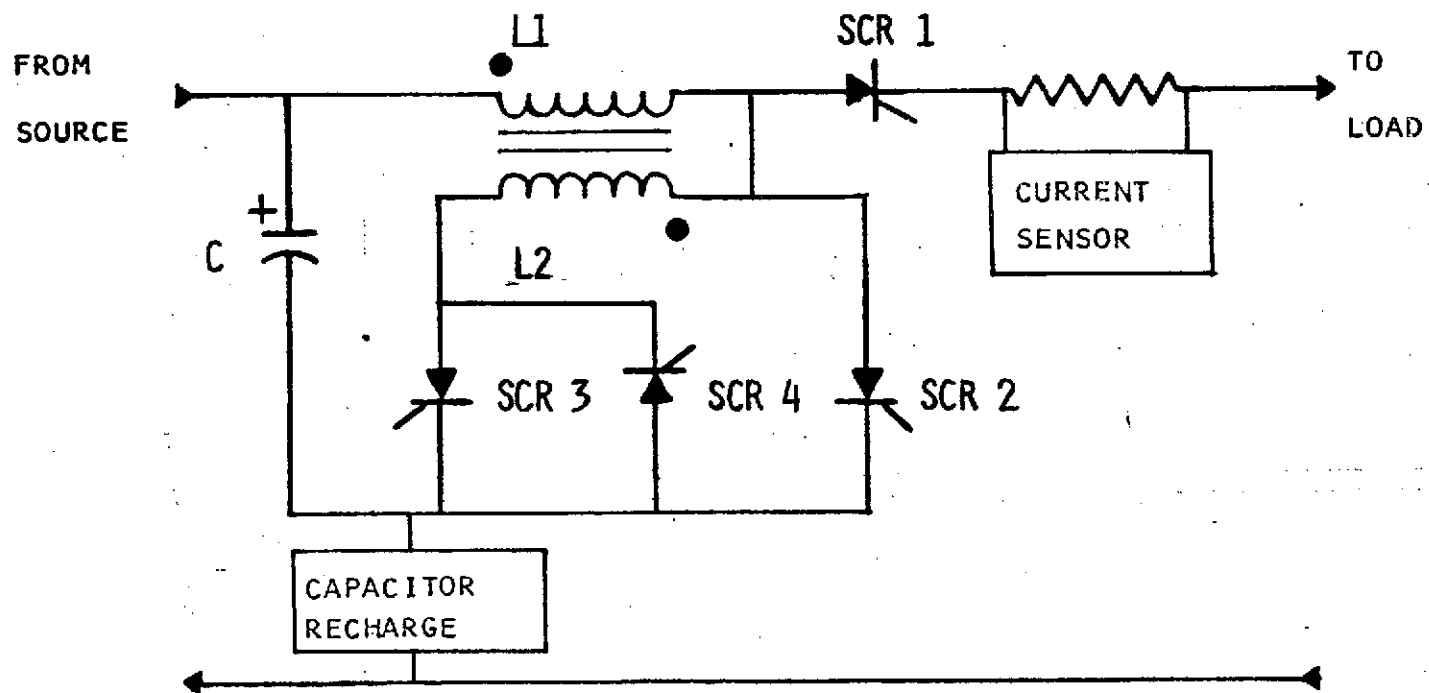


FIGURE 3 BASIC COMMUTATING CIRCUIT

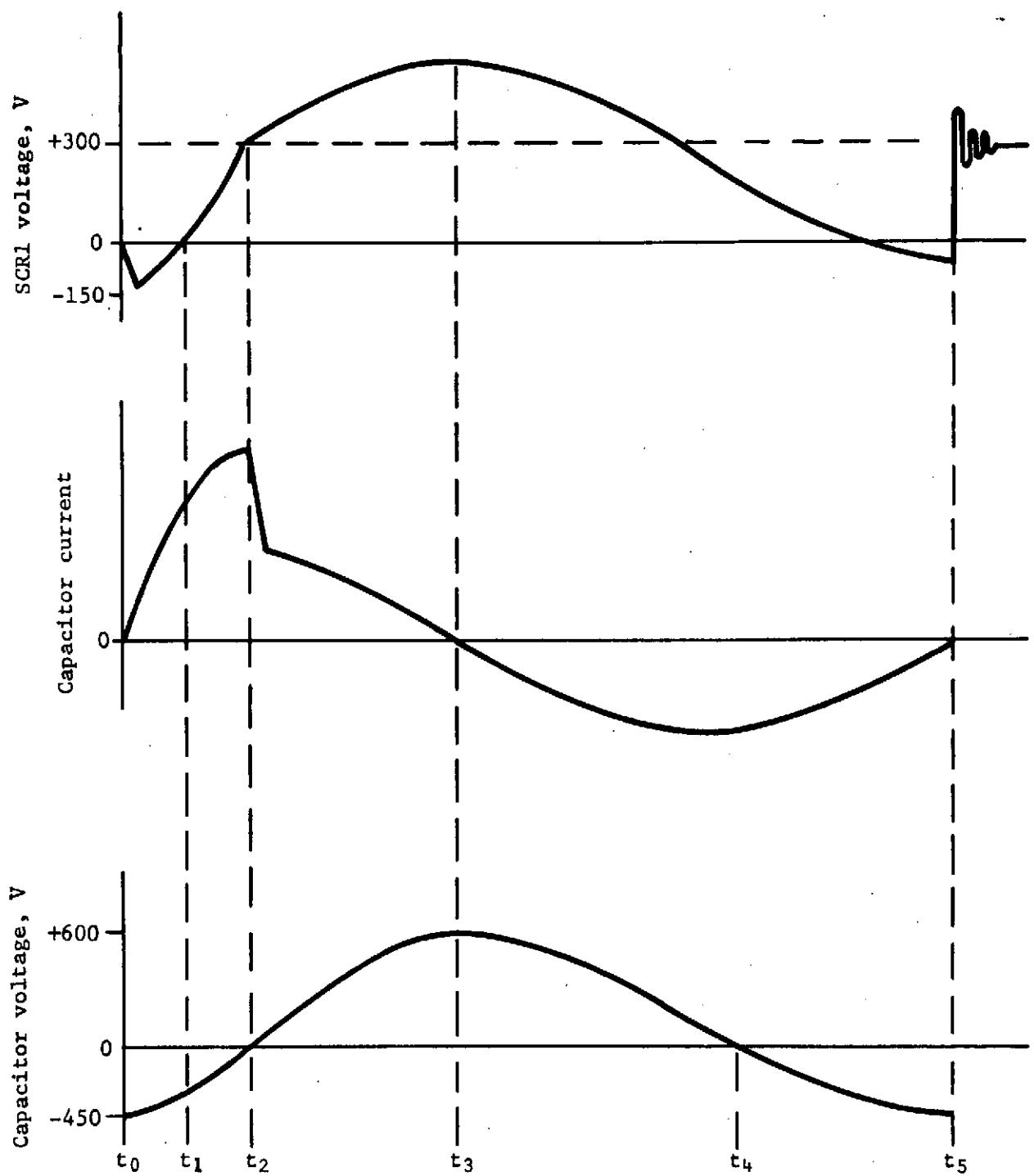


Figure 4.- Principal Waveforms of Commutating Circuit

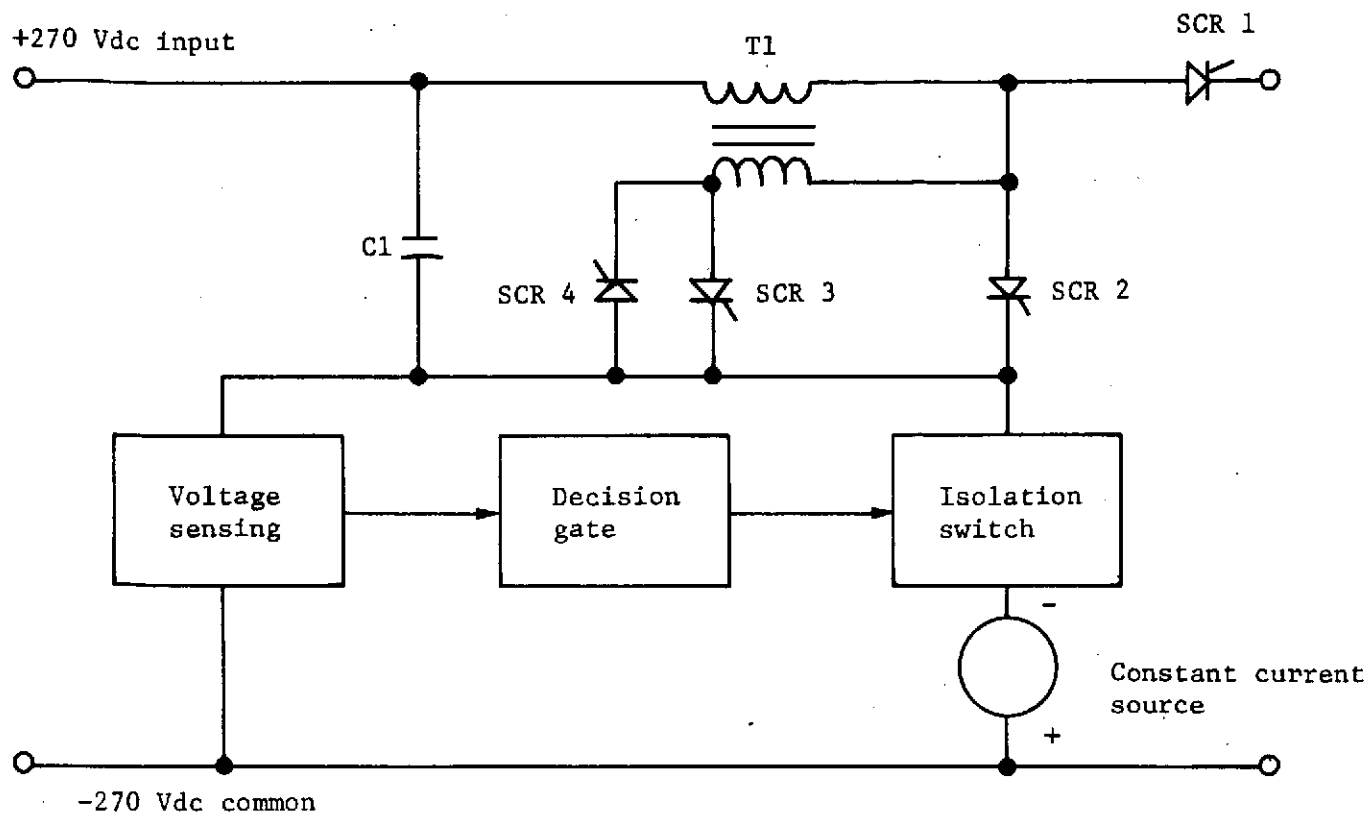


Figure 5.- Recharge Isolation Circuit Functional Diagram

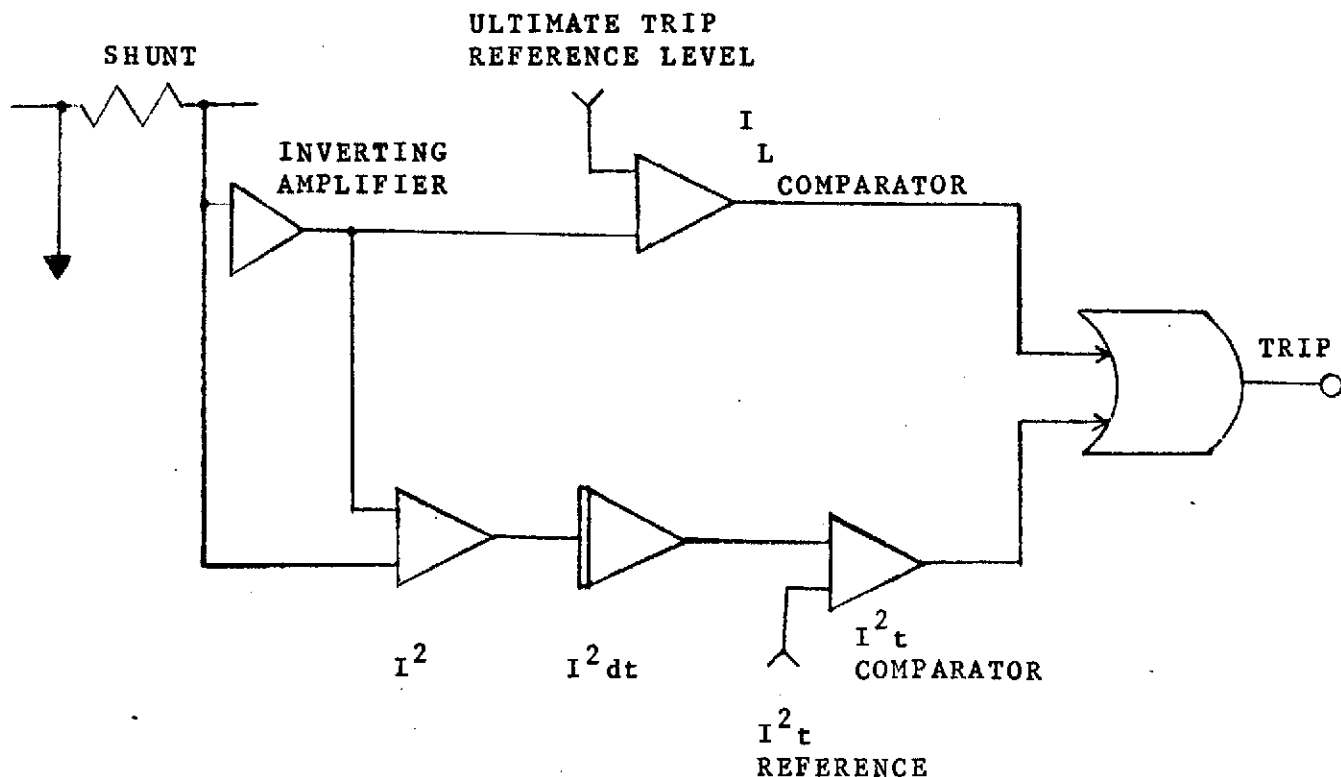


Figure 6 - Functional Diagram, Analog Fault Detection Circuits

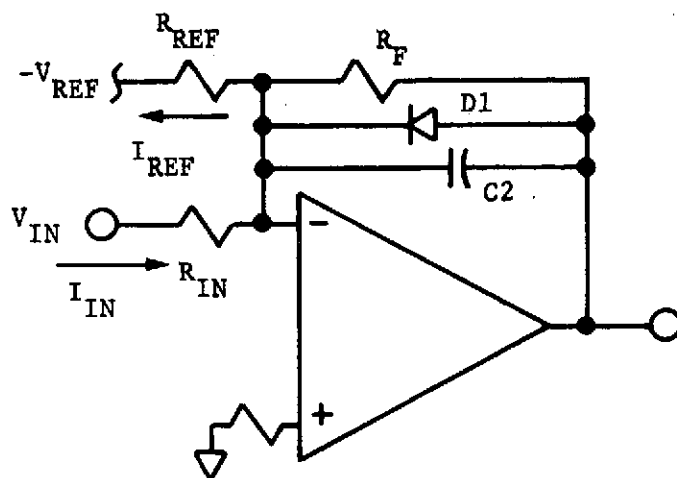


Figure 7 - Simplified Integrator Circuit Diagram

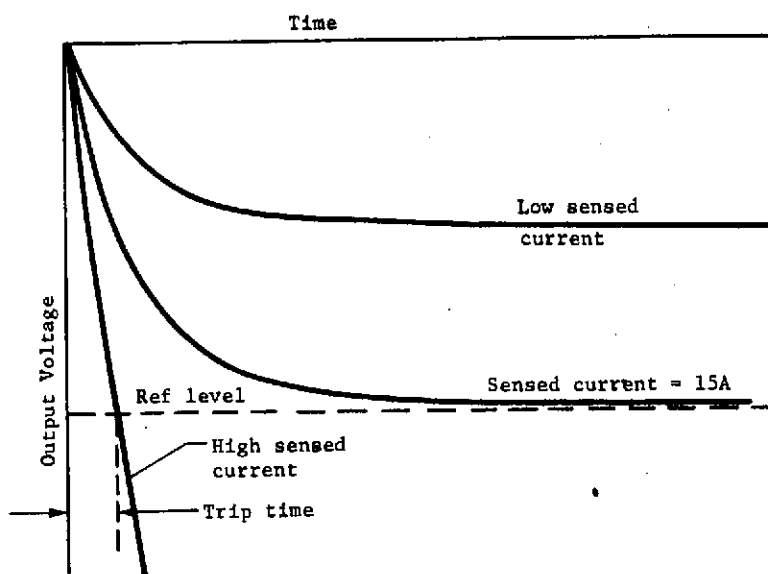


Figure 8 - Integrator Functional Waveforms

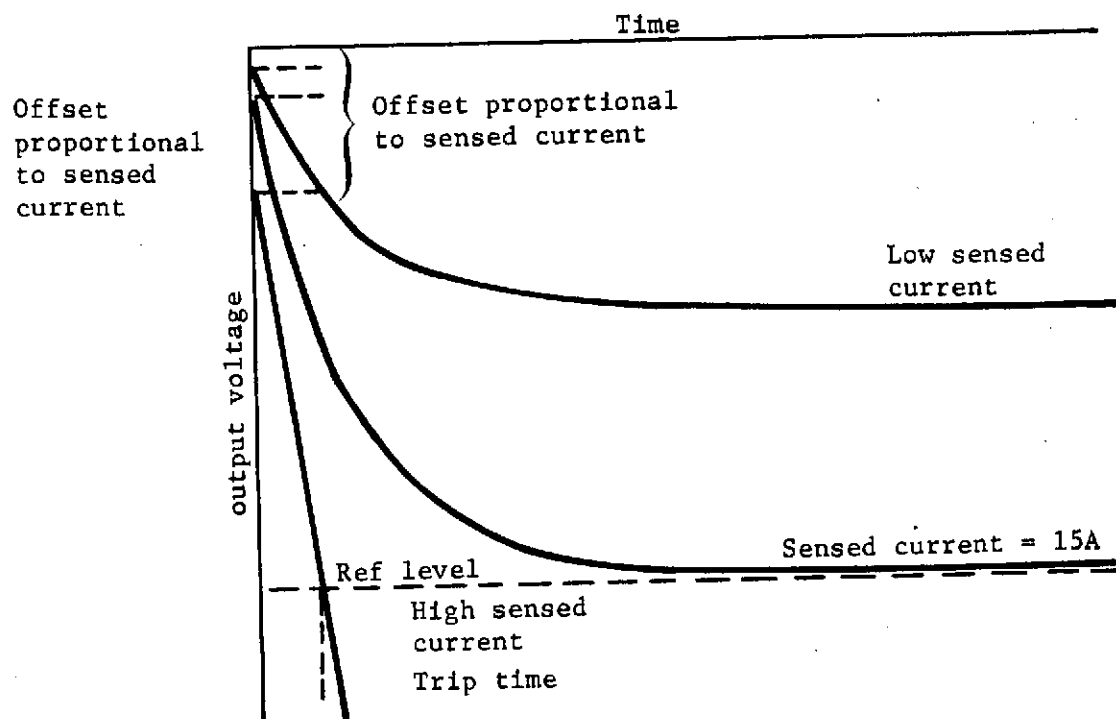


Figure 9 - Integrator Functional Waveforms, Indirect Squaring Method

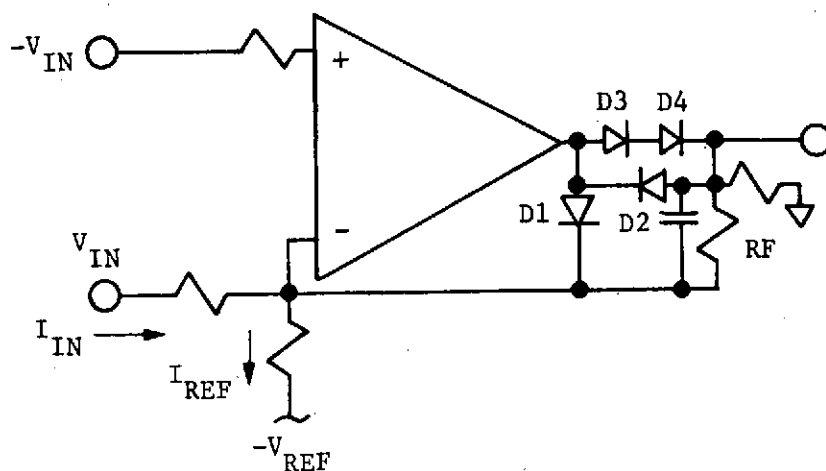


Figure 10. - Simplified Integrator Diagram With Application of Shunt Voltage to Noninverting Input

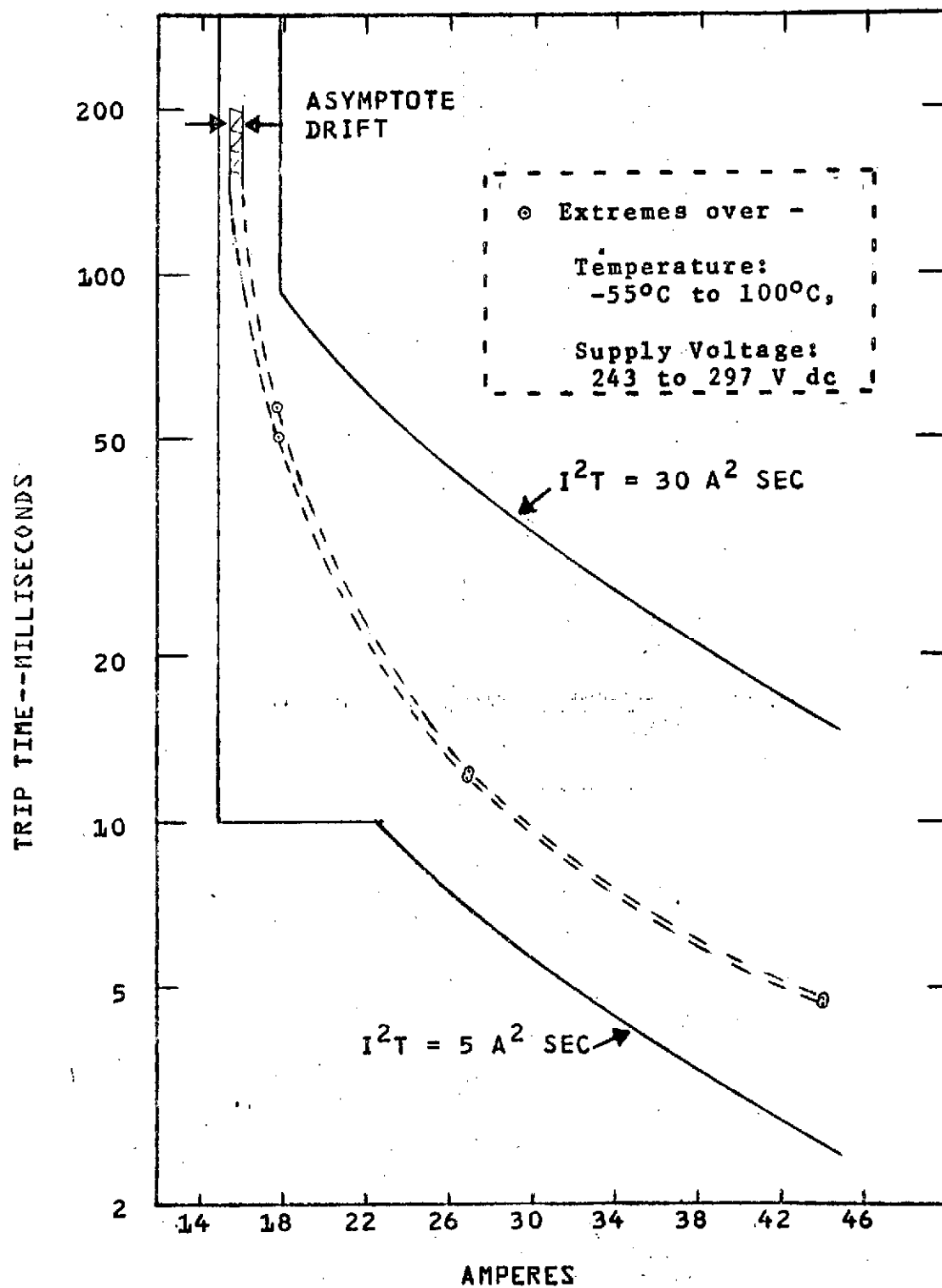


Figure 11 = Response Curve for Solid State Circuit Breaker

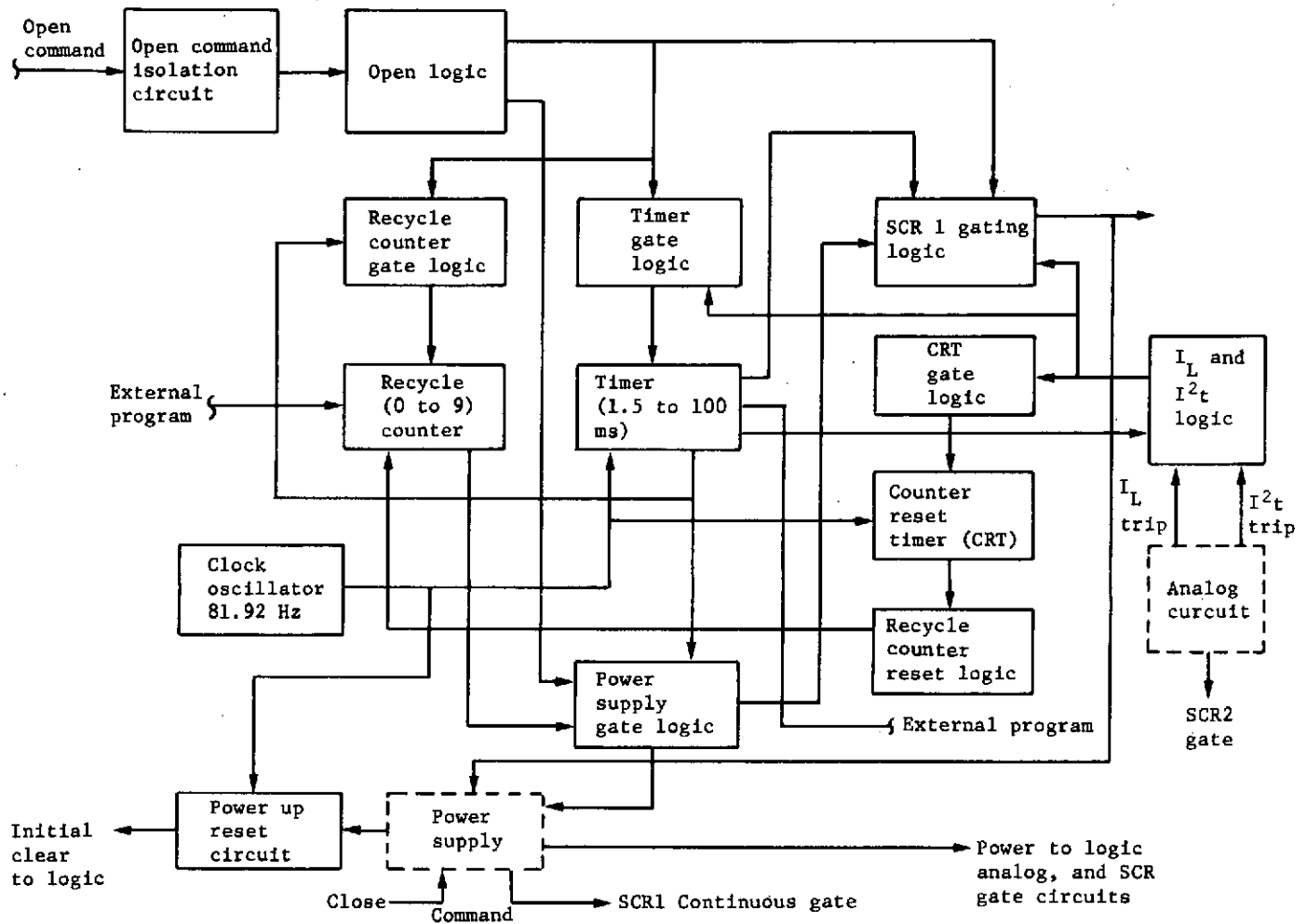
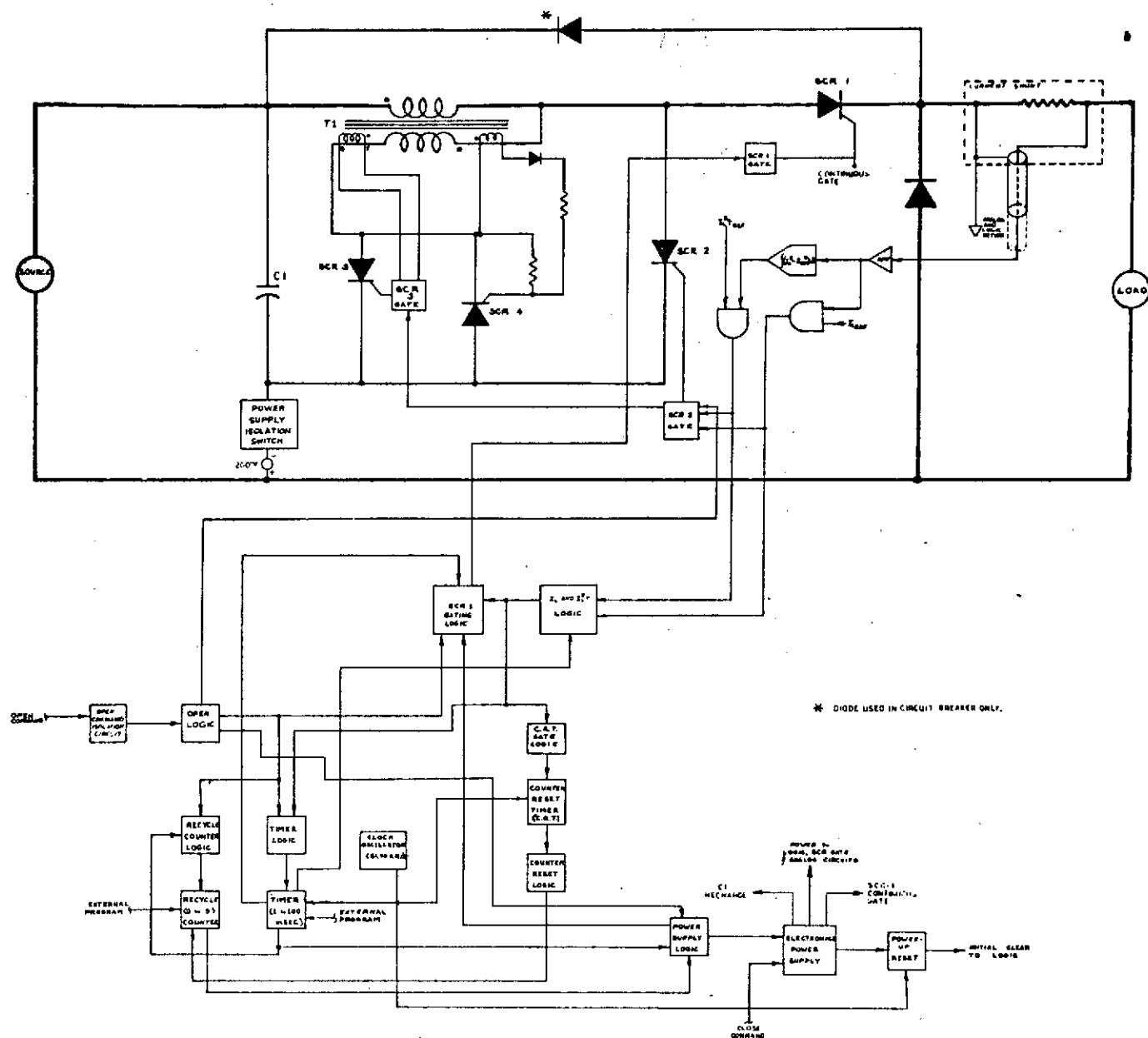


Figure 12 - Solid State Circuit Breaker Logic Block Diagram





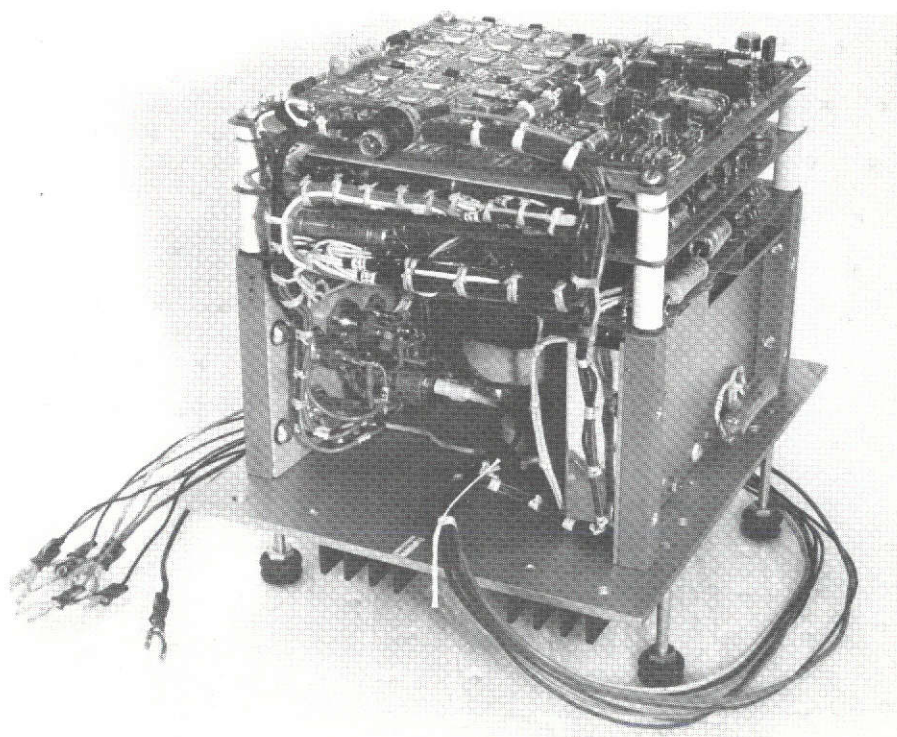


Figure 14 Solid State Circuit Breaker, Covers Removed

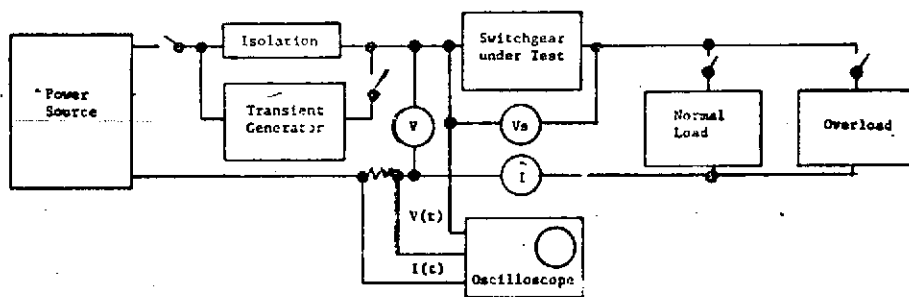


Figure 15. Simplified Schematic, System Test Tool

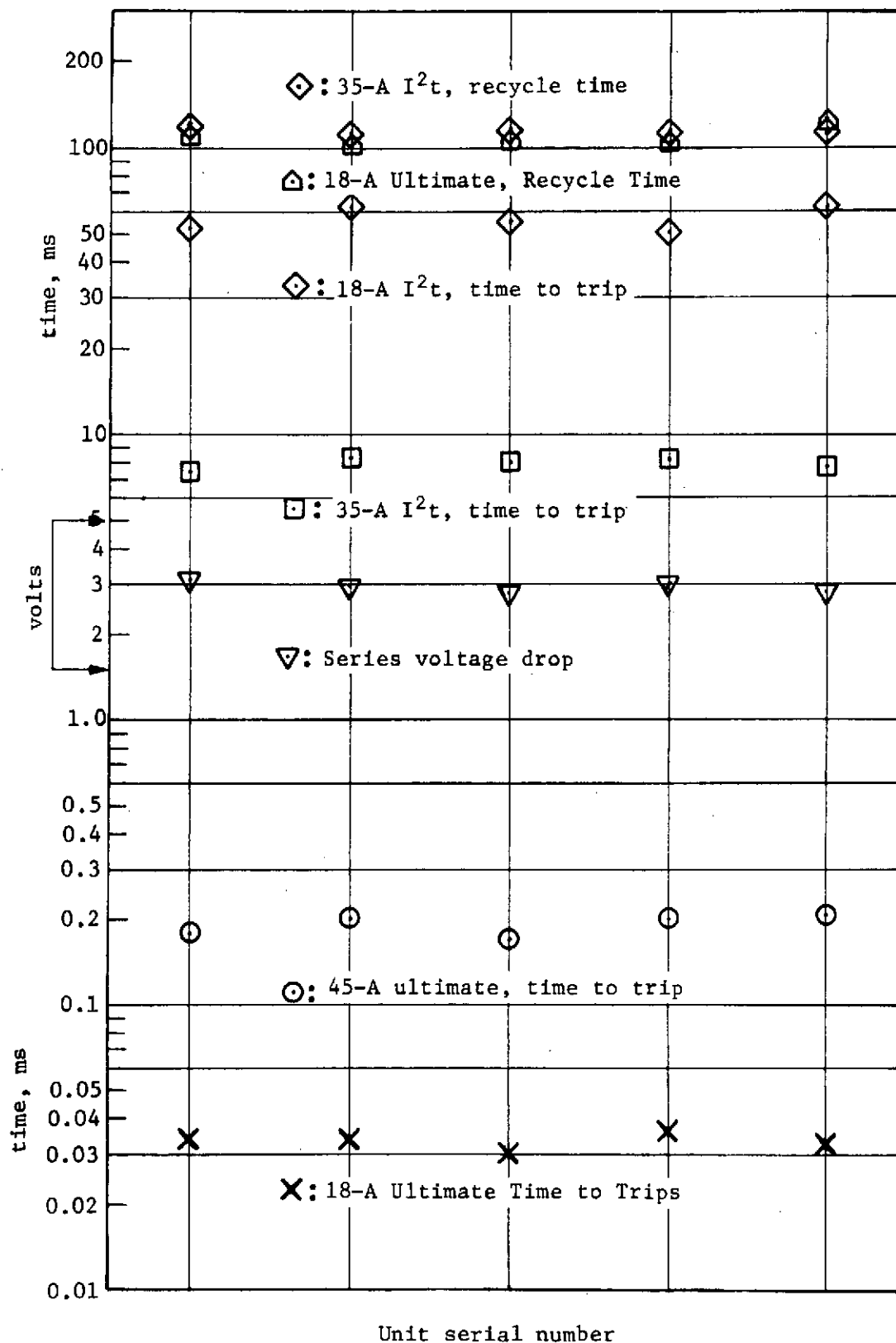


Figure 16.- Comparison of Operational Test Data

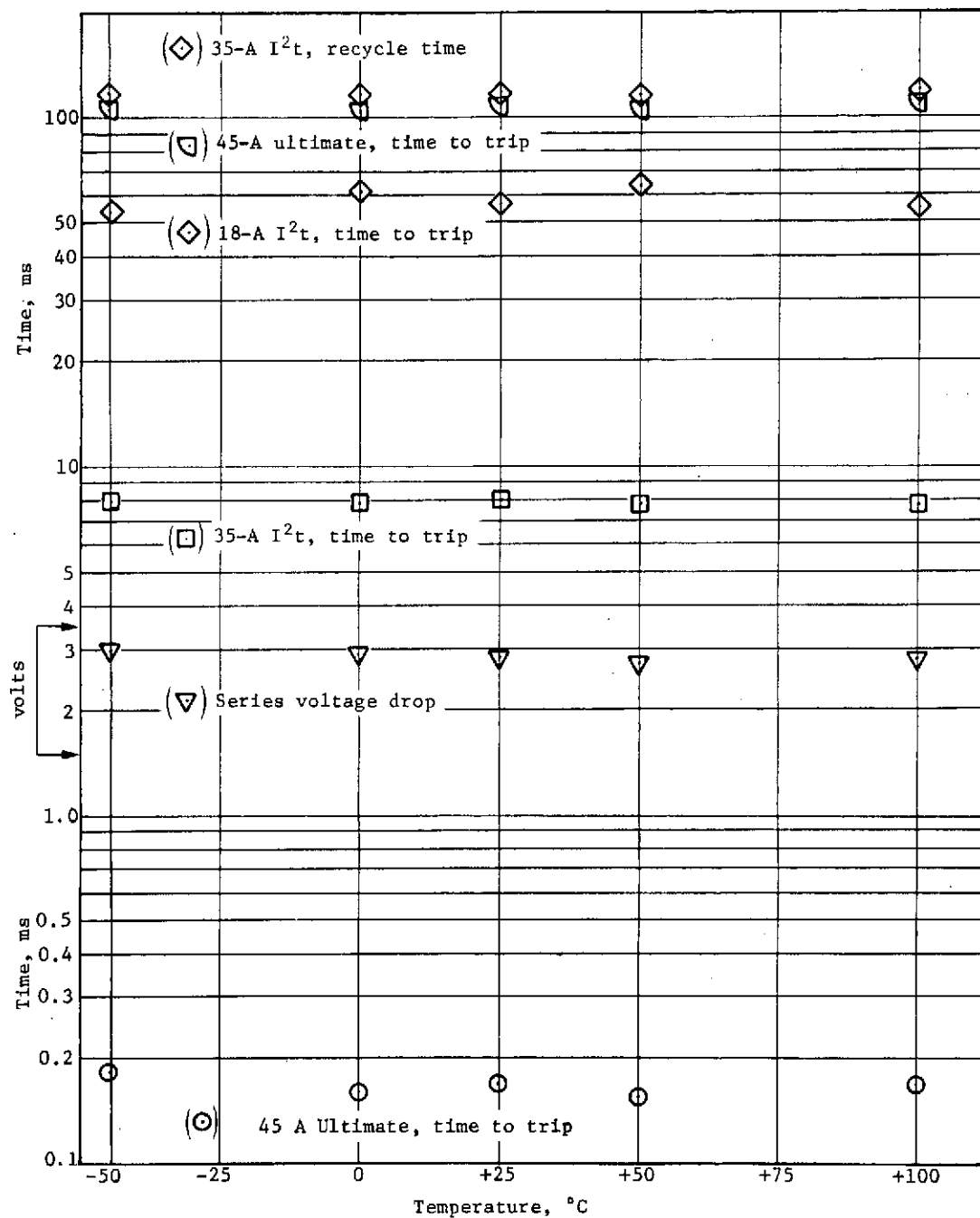


Figure 17.- Variations with Temperature, Serial Number 5  
Characterization Test